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Physical Constraints on, and a Model for, the Active Regions in Seyfert Galaxies

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ABSTRACT

We discuss several physical constraints on the nature of the Active Regions (AR) in Seyfert 1 Galaxies, and show that a plausible model consistent with these constraints is one in which the ARs are magnetically confined and “fed”. The unique X-ray index of these sources points to a large compactness parameter ($l \gg 1$). This, together with the conditions required to account for the observed optical depth being close to unity, suggests that the magnetic energy density in the AR should be comparable to the equipartition value in the accretion disk, and that it should be released in a flare-like event above the surface of the cold accretion disk. We consider the various issues pertaining to magnetic flares and attempt to construct a coherent picture, including a reason for the optical depth in the AR being ~ 1 , and an understanding of the characteristics of the X-ray reflection component and the power density spectra associated with this high-energy emission.

Subject headings: acceleration of particles — black hole physics — magnetic fields — plasmas — radiation mechanisms: non-thermal — galaxies: Seyfert

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1. Introduction

X-ray emission is a major contributor to the observed spectrum of Seyfert Galaxies, and yet the physics of the emitting region is still not well understood. The most common and (thus far) successful approach to this problem, to which we shall refer as the ‘spectral approach’ (SA), makes very simple assumptions about the geometry and/or the particle heating mechanisms, but uses a detailed microphysical approach to account for the particle-photon interactions and to derive the spectrum. This spectrum is then compared with the observations in order to place constraints on the parameters of the emitting regions. The early models assumed a non-thermal pair dominated plasma. (For a comprehensive review of non-thermal models see Svensson 1994.) However, with the more recent substantial progress made in the X-ray observation of Seyfert Galaxies (e.g., Jourdain et al. 1992; Johnson et al. 1993), it is now evident that thermal models are strongly favored by the data. Accordingly, much of the current attention is focused on thermal models (Svensson 1996a).

Aside from the question concerning the nature of the particle distribution, there is also the issue regarding the emitter’s geometry. Haardt & Maraschi (1991, 1993) argued that if most of the energy is dissipated in a hot corona overlying a cold accretion disk, then the resulting spectrum naturally explains many of the observed features in these sources. In particular, roughly half of the coronal X-ray emission is directed towards the cold disk, where it gets absorbed and re-emitted as UV radiation, which then re-enters the corona and contributes to the cooling of the electrons. Thus, the lepton cooling rate becomes proportional to the heating rate. In this case, the inverse Compton up-scattering of the UV radiation leads to an almost universal X-ray spectral index, consistent with the observations (e.g., according to Nandra & Pounds 1994, $\alpha \simeq 1.95 \pm 0.15$ for a sample of Seyfert Galaxies). The hardening of the spectrum above about 10 keV (Nandra & Pounds 1994) and a broad hump at ~ 50 keV (e.g., Zdziarski et al 1995) are accounted for by reflection of the hard X-rays in the cold disk.

However, observationally the hard X-ray luminosity, L_h , can be a few times smaller than the luminosity, L_s , in the soft UV-component. This is inconsistent with the uniform two-phase disk coronal model, because the latter predicts about the same

luminosity in both X-rays and UV (due to the fact that all the UV radiation arises as a consequence of reprocessing of the hard X-ray flux, which is about equal in the upward and downward directions). To overcome this apparent difficulty, Haardt, Maraschi & Ghisellini (1994) introduced a patchy disk-coronal model, which assumes that the X-ray emitting region consists of separate ‘active regions’ (AR) independent of each other. In this case, a portion of the reprocessed as well as intrinsic radiation from the cold disk escapes to the observer directly, rather than entering ARs, thus allowing for a greater ratio of L_s/L_h .

Recently, Stern et al. (1995) and Poutanen & Svensson (1996a) carried out state of the art calculations of the radiative transport of the anisotropic polarized radiation, for a range of AR geometries. They showed that this type of model indeed reproduces the observed X-ray spectral slope, the compactness, and the high-energy cutoff. The model has very few parameters, namely, the compactness and the temperature of the intrinsic/reprocessed radiation from the cold disk. Therefore, it appears that the model is very robust in its predictions.

On the other hand, another somewhat less common approach to explaining the X-rays from Galactic black hole candidates (GBHC) and Seyfert Galaxies, which we shall call the ‘magnetic flare’ (MF) approach, is being developed by analogy with the strong, energetic (X-ray emitting) flares observed on the Sun. A pioneering paper in this field was that of Galeev, Rosner & Vaiana (1979), who showed that the physical conditions in an accretion disk surrounding a black hole are such that magnetic fields are likely to grow to equipartition values. This magnetic field is then transported to the surface of the disk by buoyancy forces where its energy is released in a flare-like event. The magnetic flare approach is, in a sense, complementary to the spectral approach, in that it attempts to include all the relevant physics self-consistently (e.g., de Vries & Kuijpers 1992; van Oss, van den Oord & Kuperus 1993; Volwerk, van Oss & Kuijpers 1993). Unfortunately, the physics involved is quite complex and still somewhat open to debate. The resulting spectrum is a combination of time-averaged components from many different flares, and is subject to many uncertainties—clearly the MF model must invoke many more parameters, or assumptions about the magnetic field reconnection, than does the SA approach. Therefore, no detailed spectra from these events (in the case of Seyfert Galaxies) have yet been

computed.

One may argue that to make substantial progress, these two approaches need to find an overlap of self-consistency. In particular, the SA model does not specify the mechanism by which the gravitational energy dissipated within the cold disk is transported out to the optically thin corona. It is *assumed* that some process can provide the needed electron heating, and often a reference is made to magnetic fields. Moreover, the particle dynamics is ignored, imposing instead the artificial constraint that the particles are confined to a closed box. Thus, even though the SA model can reproduce the observed spectrum quite well, the situation is unsatisfactory from a broader theoretical perspective.

Correspondingly, it appears that the most important results obtained within the framework of the SA model have not been fully incorporated into the magnetic flare scenarios. For example, it is well known that the universal X-ray spectral index in Seyfert Galaxies is best explained by the inverse Comptonization of soft UV photons. This requires a relatively high value of the compactness parameter (see discussion below) in the emitting region. As far as we can tell, no work has yet been done to show (based on the physics of reconnection or some other mechanism for the transfer of energy from the magnetic field to the particles) that a specific MF model can indeed provide the needed high compactness during the active phase, though Haardt, Maraschi & Ghisellini (1994, hereafter HMG94) did use the physics of magnetic flares to account for the heating rates and the required confinement of the ARs. They showed that the compactness can be high enough during the active phase if one assumes that the entire magnetic field energy is transferred to the particles during a few light-crossing time scales. They did not, however, explicitly consider the question of how the spectrum from these highly transient phenomena is formed.

More recently, Nayakshin & Melia (1997b) considered the issue of pressure balance within the plasma trapped inside the flare during the active phase. They found that under certain conditions, a pressure equilibrium can be maintained in the source if its Thomson optical depth is $\tau_T = 1 - 2$. They also showed that the current data cannot distinguish between a spectrum comprised of a single flare component and one formed from many different flares with a range $\sim 0.5 - 2$ in τ_T . In other words, one can always find a τ_T for the spectrum assuming a single flare that

represents the composite spectrum quite well out to about 100 keV, where the quality of the data deteriorates. In addition, Nayakshin & Melia (1997c) have considered the implications of a time-dependent X-ray reflection and reprocessing by the cold disk underneath the flare. They find that due to the short lived, but very intense X-ray flux from the AR, the upper layer of the disk is compressed to a density in excess of that found in the disk's mid-plane. Under these conditions, the X-ray reprocessing leads to a temperature of the emitted UV radiation that is roughly independent of the X-ray luminosity and the overall bolometric luminosity of the source, as suggested by the EUV-soft X-ray observations (Walter & Fink 1993; Fink et al. 1994; Zhou et al. 1997). Due to the increased gas density in the compressed layer, the ionization parameter is smaller than that arising in time-independent X-ray reflection (i.e., when the X-ray source is assumed to be stationary—a condition that is clearly violated in magnetic flares). This may explain those observations of Seyfert Galaxies that suggest the presence of a nearly neutral reflector (Zdziarski et al. 1996).

These results strengthen the MF model and motivate us here to attempt to assemble the various components of this picture. We first discuss the different physical constraints imposed on the ARs by both the spectral observations and the physics of the corresponding processes, without necessarily confining our discussion to the MF model. We will then show that magnetic flares above the cold disk are probably the best candidates for producing these ARs, and we discuss the physics of the MF model in greater depth. We conclude by listing some of the unresolved issues.

2. Physical Constraints on the Active Regions

Our first task here will be to assemble the various constraints imposed on the ARs in Seyfert Galaxies from observations and theoretical considerations. In so doing, we shall first summarize the better known results, and then discuss the additional constraints that follow from various attempts to construct realistic ARs based on the idea that these may be magnetic structures, characterized by a well-defined confinement and energy supply.

2.1. Compactness of the Active Regions

The most important parameter of the AR is the compactness $l \equiv F_\gamma \sigma_T \Delta R / m_e c^3$, where F_γ is the radiation energy flux at the top of the AR and ΔR is its typical size. Note that this definition is for the local compactness, i.e., the one that characterizes the local properties of the plasma, unlike the global compactness $l_g \equiv L \sigma_T / R' m_e c^3$, where L is the total luminosity of the object and R' is the typical size of the region that emits this luminosity. It is the latter that should be compared to the observed compactness rather than the former.

Consider the following example. Assume that the emitting region is a full disk-like corona. In this case the local and global compactnesses are related in this way:

$$l \simeq l_g \frac{H_c}{R'}, \quad (1)$$

where H_c is the coronal scale height, which is unlikely to be larger than the accretion disk scale height, H_d , and so the local compactness l can be much smaller than the global one. At the same time, as suggested by the frequently observed large ratio L_s/L_h (e.g., HMG94; Svensson 1996a), the emitting region can consist of a large number of small localized areas. Since the total X-ray luminosity from these ARs should be the same as that in the model with a full corona, it is clear that the local compactness of each region must be larger than that of the full corona. In particular, depending on the ratio of the total active area ΔS covered by the ARs to R'^2 , the local compactness can be either larger or smaller than the global one. Therefore, even though the observed values of global compactness for Seyfert Galaxies lie in the range 1 – 100 (Done & Fabian 1989; but see also Fabian 1994), one cannot argue that the local compactness l should be larger than these values based on observations alone.

However, a large local compactness is strongly preferred in current pair-dominated two-phase models (e.g., Svensson 1996a; Zdziarski et al. 1996). To produce the correct spectrum, τ_T should be relatively large (~ 1). In the context of the pair-dominated two-phase model, the only mechanism for fixing the optical depth is by pair equilibrium, and thus one needs $l \gg 1$ in order to create them, in which case the optical depth of the ARs becomes a function of compactness. However, as we show in §3.3 below, the optical depth of the X-ray emitting regions may be

dominated by electrons rather than pairs. For the purposes of setting theoretical limits on the compactness parameter, this nevertheless implies the same result since both cases require $l \gg 1$.

In addition, radiation mechanisms put their own limitations on the local compactness. The fact that the X-ray spectral index for Seyfert Galaxies lies in a rather narrow range (Nandra & Pounds 1994) is most naturally explained by the approximately constant Compton y -parameter (defined in, e.g., Rybicki & Lightman 1979). Fabian (1994) shows that in order for the Compton emissivity to dominate over the bremsstrahlung one, the compactness of the plasma should be larger than

$$l \sim 0.04 \Theta^{-3/2}, \quad (2)$$

where Θ is the electron temperature in the units of $m_e c^2 / k_B$. For the typical value $\Theta \sim 0.2$, this requires that $l \gtrsim 0.5$.

Note that the gas does not necessarily need to be Maxwellian, as long as the optical depth is sufficiently large (e.g., Ghisellini et al. 1994; Nayakshin & Melia 1997a), since then the Comptonized spectrum looks very much the same for different electron distributions having the same y -parameter. Moreover, in the presence of a strong magnetic field, the synchrotron self-absorption is an efficient mechanism for thermalizing the electrons, to the extent that it becomes a more important thermalization mechanism than Coulomb collisions (Svensson 1996b; Nayakshin & Melia 1997a). Thus, constraints imposed on the compactness by the Coulomb thermalization process (Fabian 1994) can be violated.

To summarize this section, we note that all current explanations for the X-ray emission from Seyfert Galaxies require a large local compactness parameter $l \gg 1$.

2.2. Geometry, Confinement and Life Time: Magnetic Flares Required

As already discussed in the Introduction, observational evidence very strongly favors the geometry of localized X-ray sources above the accretion disk. We note that this immediately requires the active regions to be transient with a lifetime comparable to (or less than) the disk thermal time scale, $t_{th} \sim \alpha^{-1} t_h$, where $t_h = H_d / c_s$ in terms of the sound speed c_s . An integral assumption of the two-phase model is that the internal disk emission is negligible compared with the

X-ray flux of the AR, at least during the active phase (Poutanen & Svensson 1995). Assuming that a fraction (~ 1) of the total energy content in the surface area of the disk immediately below the AR is transferred into the AR, the time scale for the release of this energy must then be much shorter than t_{th} , during which time the disk's internal energy is radiated. Our calculations show that if this condition is not satisfied, then the localized ARs actually produce a *steeper* spectrum than that of a full corona, due to the enhanced internal emission from regions of the disk that surround the AR. This is an effect that is neglected in the two-phase corona-disk model. Physically, the internal disk emission provides too much cooling in this case, unless the X-ray emitting region somehow snatches heating power even from disk regions that are not directly below it, which appear to be unrealistic.

The plasma in the ARs should be confined during the active phase, otherwise the energy will be lost to the expansion of the plasma rather than producing the X-rays. Not confined, the source would expand at the sound speed (which turns out to be a fraction of c for these conditions). The lifetime of the AR would then be limited to a few light crossing times. It is not clear that the spectrum from such an expanding and short lived source can resemble anything studied thus far in the literature. The familiar gravitational confinement, operating in the main part of the accretion disk, does not work here due to several reasons. First of all, the *locally* limited Eddington compactness l is at most $\sim 50/(1 + 2z)$ for ARs with a roughly semi-spherical shape, where z is the positron number density n_+ divided by that of the protons n_p , while the relatively large Thomson optical depth $\tau_T \equiv \sigma_T n_p (1 + 2z) \sim 1$ obtained by Zdziarski et al. (1996) requires a compactness of a few hundred (if no magnetic field is involved and the particles are confined to a rigid box). Second, there is no mechanism for counter balancing a side-ways expansion of the plasma. Therefore, since there seems to be no other reasonable possibility for confinement of the AR plasma, it may be argued that a magnetic field is required to provide the bounding pressure. Any confinement mechanism will fail to confine the plasma for a time longer than about one dynamical time scale for the disk, since adjacent points with slightly different radii are torn apart on this time scale due to the disk's differential rotation.

In addition, if the pairs are important for the

model, then the lifetime of the AR should be large enough to allow establishment of the pair equilibrium. To put it another way, there should be enough time to create enough pairs if the plasma is initially optically thin and proton-dominated. We experimented with time-dependent codes in which radiation transfer is treated in the frequency-dependent Eddington approximation, and found that this condition leads to the requirement that the lifetime of the region should be roughly an order of magnitude longer than the light crossing time for the AR. In the thin disk approximation one can always satisfy both requirements as long as the size ΔR of the AR is of the order of the disk scale height H_d , since $t_h \equiv H_d/c_s \gg H_d/c$, where c_s is the local sound speed. We should also note that there can be other than pair creation mechanisms for the plasma to adjust its optical depth (see §3.3), so this constraint is only important when the optical depth is dominated by pairs.

To be consistent with the observations and the physics of the two-phase accretion disk-corona model, one needs very short lived phenomena to occur above the disk's atmosphere. In fact, the whole evolution of the AR should happen faster than the disk's hydrostatic time scale. To confine the plasma with a high compactness parameter $l \gg 1$, one needs mechanisms other than gravitational confinement. We suggest that this points to magnetic flares as the most likely mechanism for the AR formation.

3. Magnetic Flares and Accretion Disks

Galeev, Rosner & Vaiana (1979) showed that magnetic flares are likely to occur on the surface of an accretion disk, since the internal dissipative processes are ineffective in limiting the growth of magnetic field fluctuations. As a consequence of buoyancy, magnetic flux should be expelled from the disk into a corona, consisting of many magnetic loops, where the energy is stored. It has also been speculated that just as in the Solar case, the magnetically confined, loop-like structures (which we shall collectively call magnetic flares; see, e.g., Priest 1982) produce the bulk of the X-ray luminosity. The X-rays are assumed to be created by upscattering of the intrinsic disk emission.

Since then, several Solar magnetic flare workers have elaborated on this subject (e.g., Kuperus & Ionsen 1985; Burm 1986; Burm & Kuperus 1988; Stepinski 1991; de Vries & Kuijpers 1992; Volwerk, van Oss & Kuijpers 1993; van Oss, van Oord & Kuperus 1993).

Unfortunately, these models are very much more complicated than simpler plasma models that take into account the detailed interaction of particles and radiation but leave out the question of how the plasma is confined and energy is supplied. Thus, although the models invoking magnetic flares above the cold accretion disk have been viable, the detailed spectrum from such a flare could not be computed, and the model has remained somewhat of an abstraction.

An important step forward was that by Haardt, Maraschi & Ghisellini (1994), who for the first time attempted to connect the physics of magnetic flares with the observational need for localized active regions above the disk. However, the actual consideration of the magnetic field structure that confines the plasma to the AR was still missing. Furthermore, the amount of energy stored in the magnetic field has been treated as just a parameter, depending on how long and at what rate the energy is supplied to the AR. In reality, the field value is limited by the equipartition field in the disk (Galeev, Rosner & Vaiana 1979). The question of how the pressure equilibrium in the AR (important when discussing τ_T of the source) is set up has not been discussed.

One of the purposes of this paper is to pay more attention to the magnetic flare model for the X-ray emission from accretion disks in black hole systems in general, and in Seyfert Galaxies in particular. In the rest of the paper, we point out that the MF model can account for many, if not all, of the observed X-ray and UV spectral features of Seyfert Galaxies. Very importantly, we shall also demonstrate that these flares are physically consistent with the constraints imposed on the ARs discussed above.

3.1. Possible Flare Geometry

In the standard accretion disk theory, the gas density has an approximately Gaussian vertical profile, and thus it decreases very fast with increasing height. Let us also assume that the magnetic flux tube is rooted in the midplane of the disk. The “flare region”, i.e., that part of the flux tube above the accretion disk surface, is then dominated by magnetic field pressure. It is well known that a magnetic field, left to its own devices, tends to fill all the available space (e.g., Parker 1979, §8.4). For the magnetic flux tube rooted in the midplane of the disk, this means that the tube cross section expands; the tube is thick in the sense that the cross sectional radius is of the order of the tube length. The whole structure has a

roughly semi-spherical shape (Fig. 1).

We note that the observations actually require the magnetic flux tubes to be thick if they are to explain the X-ray emission from Seyferts. Indeed, if the tubes are slim, then most of the photons reflected from the disk will not re-enter the AR, but leave system. The amount of cooling of the AR due to these photons is then not enough to explain the X-ray indexes of Seyfert galaxies—from spectral modeling, it is known that the fraction of photons re-entering the AR should be relatively large, $\sim 1/2$ (e.g., Svensson 1996a).

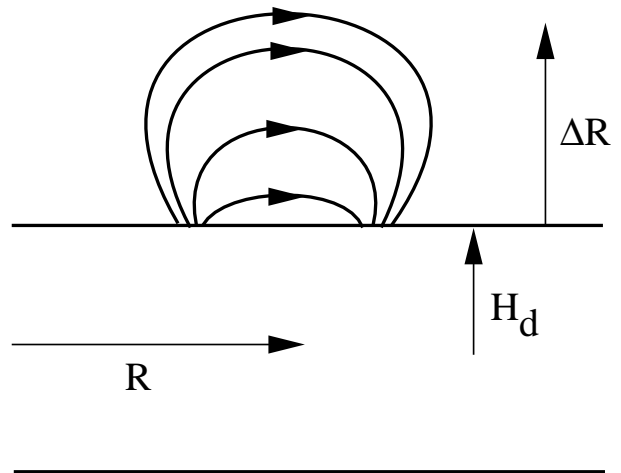


Fig. 1.— Schematic of the magnetic flare geometry above the surface of an accretion disk with scale height H_d . The radius R is measured from the black hole, and the flux tube is here shown with a vertical size (ΔR) comparable to H_d .

3.2. Maximum Compactness

We will now assume that by some process (e.g., by magnetic reconnection or dissipation of magnetic waves) the magnetic field energy is being transferred to the particles. We can estimate the maximum compactness of the AR by the following considerations. The magnetic field is limited by the equipartition value in the midplane of the disk. The size of the AR, ΔR , is of the order of one turbulent cell, which is at best of the order of the disk scale height H_d . Let us assume that the field annihilation (which provides the energy transfer to the particles) occurs on a time scale t_1 equal to the light crossing time H_d/c times some number $b \gtrsim$ a few. We will also assume that

the flare occurs at 6 gravitational radii, where most of the bolometric luminosity is produced. Using the results of SZ94, we obtain:

$$l \leq \left(\frac{1}{b}\right) \frac{\varepsilon_d H_d}{\Sigma_{\text{cr}}} \frac{\Delta R}{H_d}. \quad (3)$$

Here, the ‘critical’ column energy density is $\Sigma_{\text{cr}} \equiv m_e c^2 / \sigma_T$, where σ_T is the Thomson cross section and ε_d is the midplane energy density. Using the results of SZ94, we obtain

$$\frac{\varepsilon_d H_d}{\Sigma_{\text{cr}}} = C \times (m_p / m_e) \alpha^{-1} r_3^{-3/2} \mathcal{L} J \quad (4)$$

where $r_3 \equiv 3R/R_g$ is the radius in units of 3 gravitational radii, $R_g \equiv 2GM/c^2$ (M is the mass of the black hole), α is the standard viscosity parameter, and \mathcal{L} is the dimensionless luminosity, $\mathcal{L} \equiv L/L_{\text{Edd}}$, where $L_{\text{Edd}} = 2\pi(m_p c^2 / \sigma_T R_g)$ is the Eddington luminosity. Finally, $J \equiv 1 - (1/r_3)^{1/2}$ accounts for the assumed stress-free boundary condition at the disk’s inner edge. The constant C has the value $\sqrt{3/2}$ if the disk is gas pressure dominated, and it is $\sqrt{6}$ if the dominant pressure is due to radiation.

Taking $r_3 = 2$ as an example, we get

$$l \lesssim 400 \frac{\mathcal{L}}{\alpha b} \frac{\varepsilon_m \Delta R}{\varepsilon_d H_d} \quad (5)$$

where ε_m is the magnetic energy density $\lesssim \varepsilon_d$. HMG94 suggested that plausible values for b and α are 10 and 0.1, respectively. We can also assume that $\varepsilon_m \sim 0.1\varepsilon_d$. It is then seen that $l \gg 1$, but it is not likely to be as high as a few hundred.

3.3. Spectrum From Energetic Magnetic Flares

The two-phase model is often criticized for a lack of self-consistency: one of the most important quantities determining the spectrum—the Thomson optical depth of the AR—is either fixed in an ad hoc manner, or is said to be given by pair equilibrium. The latter may be viable if the pairs are strongly confined inside the AR and if the compactness of the region is \sim several hundred. However, a physical description of how this happen is needed in order to validate the basic assumptions of the model. Haardt, Maraschi & Ghisellini (1994) have made an attempt in this direction, but their description of magnetic flares was rather simplistic and did not provide an explanation for the observed optical depth. To address this issue in greater depth, Nayakshin & Melia

(1997b) considered the role played by pressure balance in establishing an equilibrium optical depth during the active phase of a magnetic flare. The main difference with the Solar case is that here the compactness of the flare is much larger than unity, and thus radiation pressure dominates over particle pressure (if the proton temperature is the same as that of the electrons). The conditions providing a pressure balance are therefore drastically different from those in the Sun, where the particles dictate the nature of the equilibrium. Nayakshin & Melia (1997b) assumed that the energy is supplied to the gas by magnetohydrodynamic waves. Under the conditions typical for Seyfert Galaxies, the group velocity of these waves (v_a) is expected to be close to the speed of light c . Because momentum is transferred to the gas, as well as energy, a compressional force is imposed on the plasma. The radiation pressure within the active region is approximately $\tau_T F_x / c$, where F_x is the X-ray flux leaving the source. In quasi-equilibrium the energy influx is equal to the energy outflux, and radiation pressure is equal to the momentum influx due to the magnetic waves. This then requires that the Thomson optical depth τ_T be in the range 0.5 – 2, depending on the actual geometry of the flare.

The Alfvén velocity can be used as an estimate for the group velocity of the magnetohydrodynamic waves. Taking the disk structure to be that of a standard Shakura-Sunyaev model in its radiation pressure dominated region, one can show that the Alfvén velocity v_a (at a distance of 6 gravitational radii from the black hole) is

$$\frac{v_a}{c} \simeq \frac{1}{2} \left[\frac{\varepsilon_m}{\varepsilon_d} \alpha^{-1} \mathcal{L} \tau_T^{-1} \right]^{1/2}. \quad (6)$$

It is evident that for $\varepsilon_m / \varepsilon_d$ and \mathcal{L} not too small, v_a can be quite close to c (if it exceeds c , the relativistic corrections will permit it to saturate at c only). In this estimate, we assume that the Thomson optical depth τ_T of the plasma within the flare region is entirely due to the accreting electrons. If in addition pairs are produced, then Equation (6) should be used with τ_p instead, where τ_p is the Thomson optical depth of the AR due to the electrons accreting with the protons, which further increases v_a / c . We conclude from this that v_a must be close to c for quite a broad range of the α -parameter, \mathcal{L} , and it is *completely independent* of the black hole mass M .

As already noted by Haardt, Maraschi & Ghisellini (1994), the spectrum of a magnetic flare should be

similar to that of a static active region of the same size and compactness, as long as the lifetime of the flare exceeds several light-crossing time scales. This is certainly true if pairs are not important, since the time scales for other processes that may influence the spectrum (e.g., Poutanen & Svensson 1996a) are of the order of a light crossing time. However, the life time of one single flare is short compared with the typical integration time of current X-ray instruments. Moreover, it is very likely that there are many magnetic flares present at any given moment of time. Therefore, it becomes clear that if magnetic flares are responsible for the X-ray emission from Seyfert Galaxies, the spectrum must be a composite of the contributions from many different flares. Nayakshin & Melia (1997b) tested this possibility, assuming that the energy balance is fixed by requiring the Compton y -parameter to be constant for all the flares (which is reasonable, given that y is fixed by the geometry of the two-phase model), and they summed over the spectra from flares with different τ_T . For illustrative purposes, the distribution of flares was taken to be a Gaussian over τ_T , centered on 1.14 with a dispersion of 0.7. The resulting spectrum is practically indistinguishable from that of a single flare with $\tau_T = 1.14$ up to a photon energy of about a hundred keV. The OSSE error bars are much larger than the deviations of the composite and single flare spectra, and so the current observations cannot distinguish between these two possibilities. Thus, magnetic flares can conceivably account for the observed X-ray/ γ -ray spectra of Seyfert Galaxies.

3.4. Explanation of the BBB Temperature

Nayakshin & Melia (1997c) considered the X-ray reflection/reprocessing due to a transient, energetic flare above the accretion disk to compare with other studies reported in the literature that assume a stationary state. The main difference between the two is the structure of the emitting (i.e., reprocessing) layer. In particular, since the flare lifetime is shorter than the disk thermal time scale, a pressure and energy equilibrium between the incident X-ray flux and the underlying disk is not established. A typical photon does not have sufficient time to diffuse to the mid plane of the disk during one lifetime of the flare. However, the X-ray skin, i.e., the layer that absorbs and reprocesses the X-rays, is only a tiny fraction of the whole disk, and thus a quasi-equilibrium is established within it. As a result of the incident flux, the X-ray

skin is compressed to much higher densities than the density of the undisturbed accretion disk. It turns out that the pressure and energy equilibrium of this X-ray skin yields a unique temperature $\sim \text{few} \times 10^5 \text{ K}$ *independently* of the mass of the central engine. This seems to account well for the observed independence of the Big Blue Bump temperature on the luminosity of the source (Walter 1994; Zhou et al. 1997). By comparison, a stationary, time independent reflection cannot easily explain these observations.

An additional attractive feature of the MF model is that due to a much larger gas density in the reflecting layer, the ionization parameter ($\xi \sim 20$) remains relatively small, in which case the reflected/reprocessed spectrum is indistinguishable from that of a neutral reflector, which appears to be favored by current observations (Zdziarski et al. 1996). Static X-ray reflection/reprocessing, on the other hand, may have difficulties complying with the observed low ionization parameter of the reflecting matter, since in this case the X-ray skin density is much lower. Summarizing, many of the attractive features of reflection/reprocessing in a static layer below the AR are preserved in the case of a time-dependent, short-lived magnetic flare, but the latter has the additional advantage of being able to account for the approximate universality of the BBB temperature and the low ionization fraction in the reflector.

3.5. Pair Equilibrium within the Magnetic Flares

One of the central questions in the modeling of Seyfert Galaxies has always been whether a pair equilibrium is established within the source, since this has some serious observational consequences. However, pairs have successfully eluded detection in Seyfert Galaxies. With the discovery of a high-energy break above $\sim 100 \text{ keV}$ and the non-detection of a predicted annihilation line, it has become apparent that the non-thermal power in Seyfert Galaxies, if at all present, is quite small (e.g., Svensson 1996a; Zdziarski et al. 1996, and references therein). Thus, it was concluded that the plasma is mostly thermal (e.g., Haardt & Maraschi 1991; Fabian 1994). This inference was supported by the finding that an annihilation line would not be observed from a thermal plasma because it is always hidden in the broad Comptonized spectrum (Zdziarski & Coppi 1995).

Recent work by (Zdziarski et al. 1996) suggests that in the context of a thermal pair equilibrium,

an optical depth of roughly unity is then the consequence of a large compactness (\sim several hundred). We, however, suggest that this situation is achieved by pressure equilibrium, as discussed in §3.3. In this case, the plasma consists primarily of the electrons and protons stripped from the disk, at least at the beginning of the flare, since during the magnetic energy storage phase the plasma is not sufficiently hot to provide enough hard photons that would create electron-positron pairs. Thus, in this framework, the pairs are not important in determining the spectrum from the flare, and this is again consistent with the lack of any observed pair signature.

Of course, a detailed modeling of a magnetic flare event must take into account the pair creation process which continuously produces new pairs when $l \gtrsim 10$. It is the total optical depth (i.e., the sum of the Thomson optical depths of electrons and pairs) that matters for the pressure equilibrium. If this pressure balance fixes the optical depth to some particular value ~ 1 , then clearly, compared to the no-pair case, the plasma must expand to accommodate the new particles. Let us assume that the total energy supplied to the plasma is a constant, which means that the luminosity L remains constant. Then, as the plasma expands, its compactness decreases as $1/\Delta R$ since $l \sim L/\Delta R$. Since the pair creation rate is proportional to l^2 , an equilibrium is reached at some ΔR such that the pairs are now responsible for a fraction of the total optical depth τ_T . This fraction turns out to be quite small unless the initial compactness is as high as several hundred. It is interesting to note that even flares with an initial value of l that would lead to a pair runaway (e.g., Svensson 1982) find an equilibrium configuration with a source compactness below this critical value. We intend to quantify the character of the pair equilibrium in this situation in a future publication, but we may already anticipate that a compactness as high as several hundred is only barely permitted by Equation (5), and that therefore pairs should be of relatively low importance to the dynamics and energetics of magnetic flares.

3.6. Magnetic Flares and AGN Light Curves

Several authors have suggested that magnetic flares above the accretion disk are responsible for the observed variations in the AGN and GBHC luminosity (e.g., Galeev, Rosner & Vaiana 1979; de Vries & Kuijpers 1992; Volwerk, van Oss & Kuijpers 1993; van Oss, van den Oord & Kuperus 1993, and oth-

ers). The power density spectrum (PDS) from these sources is typically a power-law (Lawrence et al. 1987; McHardy & Czerny 1987; Krolik et al. 1991). In the case of the Sun, Dmitruk & Gomez (1997) have shown that magnetic flares can naturally account for a power-law shape in the PDS with an index $\simeq 1.5$. Since in principle the flares in black hole systems may have different spatial sizes, and thus different durations and overall power, one can reasonably expect that a similar PDS may be produced by these transient events above the accretion disks in AGNs and GBHCs.

We note here that the power-law PDS should be explained by local variations of the magnetic flare properties, rather than variations occurring systematically with a changing location of the flare (compare with the rotating bright-spots model, e.g., Abramovicz et al. 1991). The observed X-ray PDS spans a wide range in frequencies, typically 10^{-5} - 10^{-3} Hz. This range corresponds to the range in radius ~ 30 , since $\Omega^{-1} \sim R^{3/2}$, where Ω is the rotational frequency of the Keplerian disk. But the local contribution to the overall luminosity goes as J/R^2 , and thus the smallest frequencies contribute less than the largest ones, in contradiction to the observed power spectrum. Only if one assumes that the luminosity of the flare is independent of its location does one obtain the right power spectrum. However, such an assumption is unphysical, since we know that the X-ray luminosity is a major component of the bolometric luminosity, and thus it should scale in the same way as the local gravitational dissipation in the disk.

Therefore, since the emission comes from a relatively narrow range in radii, it should be the flare size that varies and produces the observed PDS. Alternatively, since disturbances propagate along magnetic field lines in a strong magnetic field, and since the magnetic flux tube is thick, there can be a wide range in characteristic scales D even in one source (D is essentially the length of the given magnetic field line [see Fig. 1]). Moreover, the energy density of the magnetic field will scale roughly as $1/D^2$ (that would be so for a potential field that has no currents even at the boundary, i.e. in the footpoints). Thus, one might expect to see a power-law PDS even from a *single* event in this case. We intend to investigate this question in future work, but we caution that the analysis of the PDS is unlikely to provide any valuable information about one single magnetic flare, since at any given instant of time there should be a number

of such events. These flares occur roughly at random, and thus information about a single flare is washed out.

The complete annihilation of the magnetic field energy ε_m ($\approx \varepsilon_d$) within a volume H_d^3 during a time $b H_d/c$ provides an estimate of the single flare luminosity:

$$\frac{L_1}{L} \lesssim \frac{\mathcal{L}}{4b}, \quad (7)$$

where we have used the SZ94 accretion disk parameters with their f set equal to $1/2$. Based on similar considerations, HMG94 estimated the required number of magnetic flares to be about 10. We are therefore in agreement with this estimate, although in principle the number of less energetic or smaller flares may still be larger, since Equation (7) is only an upper limit on L_1 .

3.7. Gravity Constraints

An implicit assumption thus far has been that the magnetic flare can indeed sustain a sufficient number of protons roughly one disk height H_d above the disk. For this to be viable, we need to demonstrate that the gravitational energy of the protons trapped inside the flux tube is very much smaller than the magnetic field energy. The latter is at most the total thermal energy of the disk immediately below the flare, while the former may be estimated as $E_{\text{grav}} \sim 3^{-1}(\tau_T/3r_3)(m_p c^2/\sigma_T)(H_d/R)^2 H_d^2$. Using expressions from SZ94 for $r_3 = 2$, we see that

$$\frac{E_{\text{grav}}}{\varepsilon_d H_d^3} \simeq 2 \times 10^{-2} c^{-1} \alpha \tau_T \mathcal{L} \ll 1. \quad (8)$$

which satisfies the constraint. As before, $\tau_T \simeq 1$ is the Thomson optical depth of the material trapped inside the flux tube.

3.8. Stability of the Accretion Disk

The nature of accretion disk instabilities has received a great deal of attention (for recent references, see Chen 1995). While not attempting to consider this question in detail here, we can make several comments on the stability of the MF model.

Magnetic flares may be viewed as an additional channel by which energy can be transported out of the disk. Of course, in the standard disk model, the dissipated gravitational energy is lost directly to radiation. Since the time taken by a photon to diffuse

outward from the midplane to the disk's surface is a very strongly increasing function of the optical depth, it is conceivable that under some conditions the energy transported by the magnetic field is greater than that due to the radiation. The total energy content of the disk plus corona system is then expected to be lower than that of the standard theory, though with the same luminosity, and such a situation leads to greater stability (e.g., SZ94). Although it is not clear what role advection would have in such a model, it is expected that magnetic flares may help to quench some of the disk instabilities encountered in standard models.

3.9. Remaining Questions and Problems

We have seen that magnetic flares are physically consistent with the multi-wavelength spectra of Seyfert Galaxies. Very importantly, the MF model seems to account for several observed characteristics that cannot be easily reconciled with a picture in which the ARs are static. However, a host of unanswered questions and problems remain.

First, accretion disk flares have been considered only in a highly schematic fashion thus far. Unfortunately, the physics of magnetic energy release in a non-static and turbulent gas is not well known, other than the fact that it must happen, as is seen in the Sun. In addition, a detailed model of the magnetic flare should also include a consideration of all the relevant aspects of magnetic flux tube formation in the underlying turbulent disk, a problem that also has not been solved. This, however, does not mean we can ignore the magnetic flare model for the X-ray emission in Seyferts. Instead, additional studies are called for, especially in view of the fact that very recent observations of Solar flares seem to support much of the current theoretical thinking in this area and are generating enthusiasm among solar theorists (e.g., Innes et al. 1997, Klimchuk 1997).

Another major unresolved issue is how the disk viscosity is connected to the magnetic field. If we knew this relationship, we would be able to eliminate α or ε_m from Equation (5), and thus get better constraints on the maximum compactness of a magnetic flare. This follows from the fact that the structure of a cold disk is quite sensitive to the viscosity law. In addition, viscosity figures very prominently in the physics of magnetic flux tubes (e.g., Vishniac 1995).

4. Conclusions

In this paper we have attempted to address the problems that arise when physical constraints are imposed on the active regions thought to exist in the two-phase corona-accretion disks in Seyfert Galaxies. We showed that these regions should necessarily be highly transient, i.e., evolve faster than one thermal disk time scale due to spectrum formation constraints. A consideration of the plasma confinement lead us to require an overall magnetic field with a stress much larger than the X-ray radiation pressure. Furthermore, putting these constraints together, we concluded that the magnetic flare model appears to be consistent with the type of transient active regions required by the observations. We then proceeded to show that the model is probably capable of explaining the observed optical depth, X-ray reflection and UV reprocessing implied by the data, and the observed power-law power density spectra. Finally, we discussed the unresolved issues that need to be investigated in future work.

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